Consequences of large scale hydrographic alteration during the Deepwater Horizon Oil spill on subtidal oyster populations

Technical Report

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Introduction

Within most estuaries in the Northern Gulf of Mexico and Atlantic Ocean, the Eastern Oyster (*Crassostrea virginica*) forms reefs that provide ecosystem services that benefit human societies, in the form of enhanced commercial fisheries, estuarine habitats, improved water quality, and shoreline stabilization, among others (Grabowski et al. 2012). During the 87 day long Deepwater Horizon Oil Spill, vast quantities of Mississippi River water were released into two estuarine basins (Barataria Bay and Black Bay/Breton Sound) in response to the approach of oil from offshore waters. These releases were unusual in timing and volume when compared to other years (Figure 1). We assessed the impact to subtidal oyster populations to this novel response action using three methods: (1) comparison of fisheries independent post-spill densities to a pre-spill temporal baseline, with two alternative areas of influence ("Fisheries Temporal" and "Fisheries in freshwater polygon Freshwater Polygon"); (2) comparison of oyster density collected during natural resource damage assessment (NRDA) sampling between the area of maximal freshwater impact and reference areas in the two basins ("NRDA spatial"; and (3) estimation from a dose-response model derived from an analysis of an *in-situ* mark and recapture study conducted in 2010 to assess the relationship between salinity and oyster mortality ("NRDA/Nestier Tray"). These approaches all show larger oyster losses in the areas affected by low salinities due to high river water levels in 2010. The relationship between oil exposure and abundance of subtidal oysters was also examined by evaluating relationships between abundance of each age class (adult, juvenile, and spat) and oyster tissue polycyclic aromatic hydrocarbon(PAH) concentrations, oiling (as measured in terms of co-located sediment total PAH (tPAH)) and oil-on-water (days, frequencies as well as presence/absence).

Injury Quantification Methods

Subtidal oyster losses were evaluated using field measurements of oyster abundance after the spill, historical information from the state of Louisiana on oyster abundance, mapping of oyster cover conducted by NRDA field studies (Roman and Stahl 2015), field observations of oyster survival over time (Nestier tray studies), along with salinity modeling to interpret oyster abundance observations over space and time, and literature information on survival between life stages (Roman and Hollweg 2015).

All approaches to estimating *Deepwater Horizon*-related subtidal oyster injury used field-collected abundance and percent cover data.

Data Sources

The Fisheries Temporal approach used data from Louisiana's oyster fisheries independent monitoring program, which focuses only on public subtidal oyster grounds (Figure 2). These data were collected by the Louisiana Department of Wildlife and Fisheries (LDWF) in June and/or July from 2006-2010 as part of their annual oyster stock assessment. Depending on the year, field teams used 0.25 m^2 or 1.0 m^2 quadrats. Teams sampled at 8 sites in Barataria Bay and 32 sites in Black Bay/Breton Sound (LDWF Stock Assessment 2006 through 2010).

The other two approaches relied on data collected under the *Deepwater Horizon* NRDA from July to October 2010. (Figure 2) Sampling consisted of up to eight diver-collected quadrats at 200 m^2 study sites in Barataria Bay (eight sites) and Black Bay/Breton Sound (eight sites) (Figure 2). Because this study focuses on subtidal oyster injury, sites where oyster habitat typical of nearshore or intertidal oysters was observed were excluded. The NRDA sample sites included some of the regularly sampled LDWF stock assessment sites plus additional Barataria Bay sites periodically sampled by LDWF. NRDA quadrat sampling locations were randomly generated from oyster habitat areas identified from side-scan sonar surveys conducted at each site. Field teams used both 0.25 m^2 square and 1.0 m^2 quadrats, with the larger size used where oyster habitat was less contiguous. Quadrat samples were enumerated by size class for spat-, seed-, and market-sized oysters using the same definitions applied to the LDWF data. Density results from 0.25 m^2 quadrats were scaled to estimate density per 1.0 m^2.

To assess the relationship between salinity and oyster survival, we analyzed "Nestier tray" data from LDWF from 2007 through 2012. At the beginning of each year, LDWF deployed a series of 70 x 70 x 7.6 centimeter trays with 20 seed-sized oysters attached. These trays were placed at a range of distances from the river diversion structures.

All four approaches used oyster percent cover data from multiple field sampling plans conducted under the DWH NRDA and a survey conducted by the Louisiana Department of Wildlife and Fisheries (Roman and Stahl 2015).

Exposure to *Deepwater Horizon*-related river water releases was characterized using modeled daily average salinity predictions derived from extensive local salinity measurements at monitors and sampling stations. Salinity levels were calculated for each day between April 27 and September 15, as this is when the water from the structures would have been flowing into the study area. Grid cells in the model were considered affected by low salinity if the number of consecutive days with salinity <5 parts per thousand (ppt) in 2010 was more than 30 days longer than at the same location during historical baseline conditions (MacDonald et al., 2015). The area of freshwater influence was determined by comparing the area affected by low salinity water in 2010 to conditions in prior years, which represent conditions that would have occurred without the spill (Rouhani and Oehrig, 2015a). The area of injury was determined by the area affected by the river diversions multiplied by the oyster percent cover; this area is where oysters would have been expected to survive in a typical year.

Injury Calculations

The injury calculation approaches we employed require four basic steps: 1) establishing baseline conditions of oysters unaffected by the freshwater diversion openings; 2) identifying the areas exposed to freshwater from the 2010 diversion openings; 3) comparing post-spill densities against baseline densities; and 4) scaling spill-related density changes across all oyster habitat in the exposed areas.

For the NRDA/Nestier approach, the number of oysters lost per m^2 was determined as the product of the average change in the survival rate in 2010, the area of oyster habitat experiencing decreases in survival in 2010, and the average baseline density estimated from the NRDA sites. Figure 3 illustrates the conceptual approach used to calculate these losses. Using Nestier tray data to estimate death due to river water releases is considered the preferred method because it uses observed relationships between salinity and oyster death in the basins of interest and observations of oyster abundance taken from those same areas. This analysis combined NRDA 2010 abundance data with the relationship between exposure to freshwater and expected oyster death, derived from annual LDWF Nestier tray studies to identify areas likely to have experienced decreased survival due to fresh water from the Davis Pond and Caernarvon structures. Nestier tray survival and location-specific salinity data covering April through September were combined across both Barataria Bay and Breton Sound basins and used to develop a relationship between salinity exposure and oyster survival (Figure 5).

We used the following equation to calculate the oyster loss for the NRDA/Nestier method:

$$Loss = \Delta Survival\ x\ Density_{baseline}\ x \sum (Impacted\ Area_{stratum}\ x\ \%\ Cover_{stratum})$$

We also calculated oyster loss using two additional methods: the NRDA Spatial approach and approaches that apply Louisiana's Fisheries independent monitoring data. The NRDA Spatial approach assessed oyster density differences between areas highly exposed to freshwater and areas less exposed (inside vs. outside polygons of influence shown in Figure 4), using data collected under the *Deepwater Horizon* NRDA in 2010. The "Fisheries Temporal" and "Fisheries in Freshwater Polygon" approaches quantified injury by comparing abundance in 2010 to those in prior years, both for the area of impact (freshwater polygon), and basin-wide, using annual fisheries independent data collected by the state of Louisiana.

All approaches quantified injury by oyster size class (market, seed, spat) and by basin (Barataria Bay and Black Bay/Breton Sound). Oyster losses were scaled by the percent cover of oyster habitat in those basins.Losses were estimated by size class and converted to market equivalent oysters using literature survival information (Roman and Hollweg, 2015).

Results

The timing, volume, and duration of the low salinity water from these response actions were unusual compared to the years prior to the spill (2006-2009) (Figure 1), leading to very large areas (483 km^2 of Barataria Bay and 362 km^2 of Black Bay/Breton Sound) that experienced atypical low salinity conditions in the summer of 2010 (Figure 4). These very low salinity levels lasted at least one month longer than the average duration of low salinity in the baseline years 2006-2009 (Rouhani and Oehrig, 2015). Consistent with oyster cover maps presented in Roman *et al.* (2015), the freshwater impact area covered 199 and 280 km^2 (a total of 479 km^2) of oyster habitats in Barataria Bay and Black Bay/Breton Sound, respectively (Rouhani and Oehrig, 2015).

All approaches show declines in the oyster population in the areas affected by river water releases (Table 1). When average daily salinity conditions dropped below 5 parts per thousand for more than 30 consecutive days between April and September, substantial numbers of oysters were killed, as shown by over a decade of data collected in these zones by the state of Louisiana (Rouhani et al. 2015, Rouhani and Oehrig 2015, Powers et al. 2015). Observations from NRDA Spatial, the Fisheries Temporal, and Fisheries in Freshwater Polygon approaches confirm this finding. Oyster abundance in 2010 was very low in many locations within the areas affected by these river water releases (Figure 6), and dropped to zero over most of these areas in 2011.

Based on the preferred assessment approach (NRDA/Nestier), an estimated 2.7 billion adult equivalent oysters were killed by river water releases. The number of adult equivalent oysters lost was calculated by adding up numbers killed in each size class and adjusting spat and seed numbers for the proportion that would have been expected to survive to adults.[1] Over the 5 year lifespan of these oysters, had they not been killed, they would have produced a total of 69 to 195 million pounds of fresh oyster meat (wet weight). Approximately 60 percent of that total represents an estimate of the weight of the oysters directly killed, and the remaining 40 percent represents additional growth of adult oysters over the rest of their lifespan that did not occur because they were killed. The growth portion is less than the weight of the direct kill because oyster harvesting limits the potential future growth of subtidal oysters. These losses were evaluated using field measurements of oyster abundance after the spill, historical information from the states on oyster abundance, mapping of oyster cover conducted by NRDA field studies, field observations of oyster survival over time (Nestier tray studies), along with salinity modeling to interpret oyster abundance observations over space and time, and literature information on survival between life stages (Roman and Hollweg, 2015).

Fisheries independent data from before and after the spill period has been summarized by Grabowski et al. (2015) and indicate that the area affected by releases of river water (especially Black Bay) showed reduced abundance of oysters after the spill. Use of the fisheries independent data ("Fisheries Temporal" approach) provides the upper estimate of losses (3.2 billion adult equivalent oysters killed), if the difference between oyster densities in 2010 and prior years is applied throughout all of the mapped oyster habitat in each basin. Comparing the 2010 fisheries independent data on oyster densities to historical values limited to the area of freshwater impact (freshwater polygon) provides the lowest estimate of losses (1.1 billion adult equivalent oysters killed).

The design of the NRDA subtidal oyster studies was intended to evaluate abundance of oysters throughout the area where oil was observed on shorelines and surface waters. While toxicity studies have demonstrated that exposure to oil in water from the DWH spill could also have potentially harmed oysters (Morris et al. 2015), confirmation of such exposure is limited (Oehrig et al. 2015b). In addition, statistical analyses attempting to relate oyster densities with NRDA-collected data on oiling (measured in terms of co-located sediment TPAH) and oil-on-water (days, frequencies, and presence/absence) did not support a discernable association between exposure to oil and subtidal oyster densities.

Conclusions and considerations

[1] For this purpose, 30% of spat-sized oysters and 56% of seed-sized oysters are estimated to survive to adulthood (Roman and Hollweg, 2015).

Synthesis and spatial analysis of salinity observations from 2006 to 2011 revealed large scale alterations of salinity in 2010 compared to pre-spill averages (2006-2009). A substantial portion of both basins (483 km^2 of Barataria Bay and 362 km^2 of Black Bay/Breton Sound) experienced prolonged periods of very low (< 5 ppt) salinity in 2010 that lasted at least 30 days longer than the average duration of low salinity in 2006-2009.

Between 1.1 and 3.2 billion subtidal oysters (adult equivalents) were lost in 2010 (Table 1) over an area of 118,000 acres or 479 square kilometers)-(Rouhani and Oehrig, 2015a). Summing the weight of lost oysters from each size-class over time would equate to an equivalent biomass of 69 to 195 million pounds of fresh oyster meat lost due to mortality from freshwater exposure.

Sources of uncertainty in calculating the number of subtidal oysters killed by freshwater come from variations in salinity during the different baseline years (and uncertainty around what salinities would have been in 2010 had the spill not occurred), variations in responses to salinity between Nestier trays exposed to similar salinity conditions, variations in observations of oyster cover over the areas of concern, variation in abundance of oysters outside the area of freshwater influence as representative of pre-spill oyster abundance, and uncertainty in literature-derived assumptions about oyster growth and survival between life stages (MacDonald et al. 2015, Rouhani et al. 2015, Powers et al 2015, Roman and Hollweg 2015, Stahl et al. 2015). However, by using a series of different methods and multiple data sets, we consistently find that post-spill densities are lower than both temporal and spatial baseline comparison density estimates.

In the analysis of the relationship between oyster abundance and environmental factors, salinity differences from prior years were far more important in explaining observed oyster abundance than temperature variations from prior years and other variables such as disease prevalence, precipitation, or harvest closures. The scale of this loss is sufficient to pose recruitment problems for oysters in these areas for several years – a pattern evident in post spill monitoring. The efficacy of the large scale response action of altering hydrographic conditions during the summer oyster growth period should be examined in light of the major perturbation to oyster communities.

Tables

Table 1. Estimates of subtidal oysters killed as a result of lowered salinities during summer of 2010 using four approaches

Approach	Salinity Threshold	Oyster Losses in 2010 (10^6 Oysters) Market Equivalent	Oyster Losses in 2010 (production foregone)
Fisheries Temporal Assess.	--	3,169	195
NRDA Spatial Assess.	5 ppt	1,164	71
Fisheries in Freshwater Polygon		1,131	69
NRDA/Nestier Tray		2,694	165

Figures

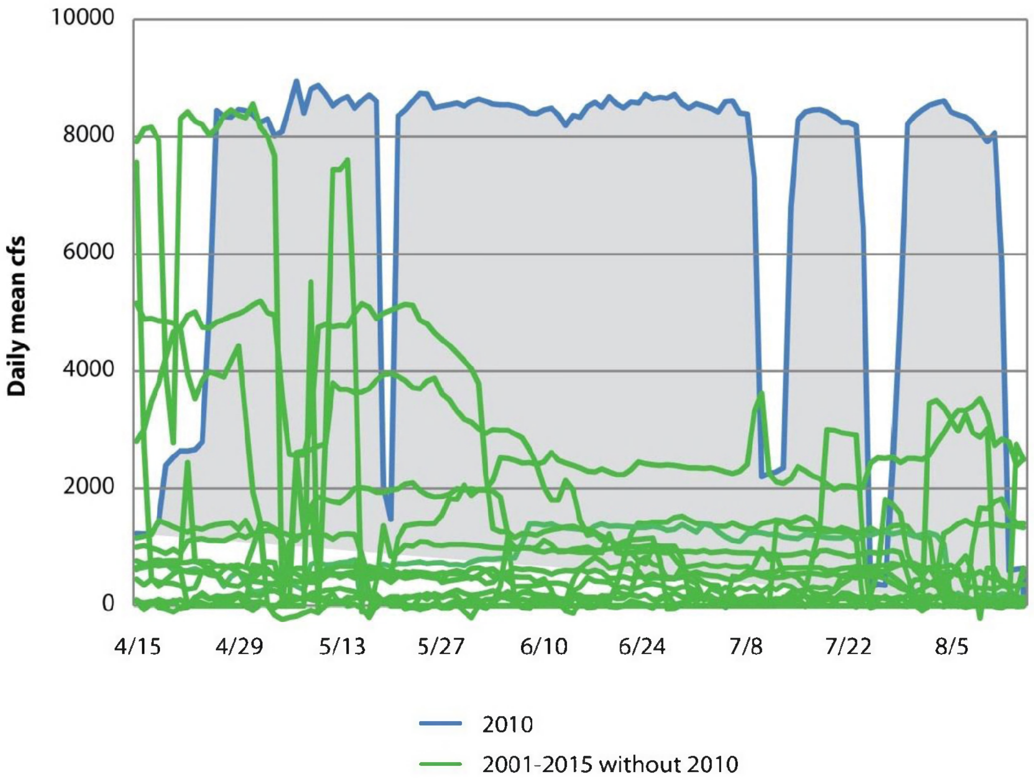

Figure 1: Release of river water through the Carnaervon Discharge in 2010 (blue) vs other years (2001-2015 without 2010) (green). Volume and timing of releases was unusual in 2010.

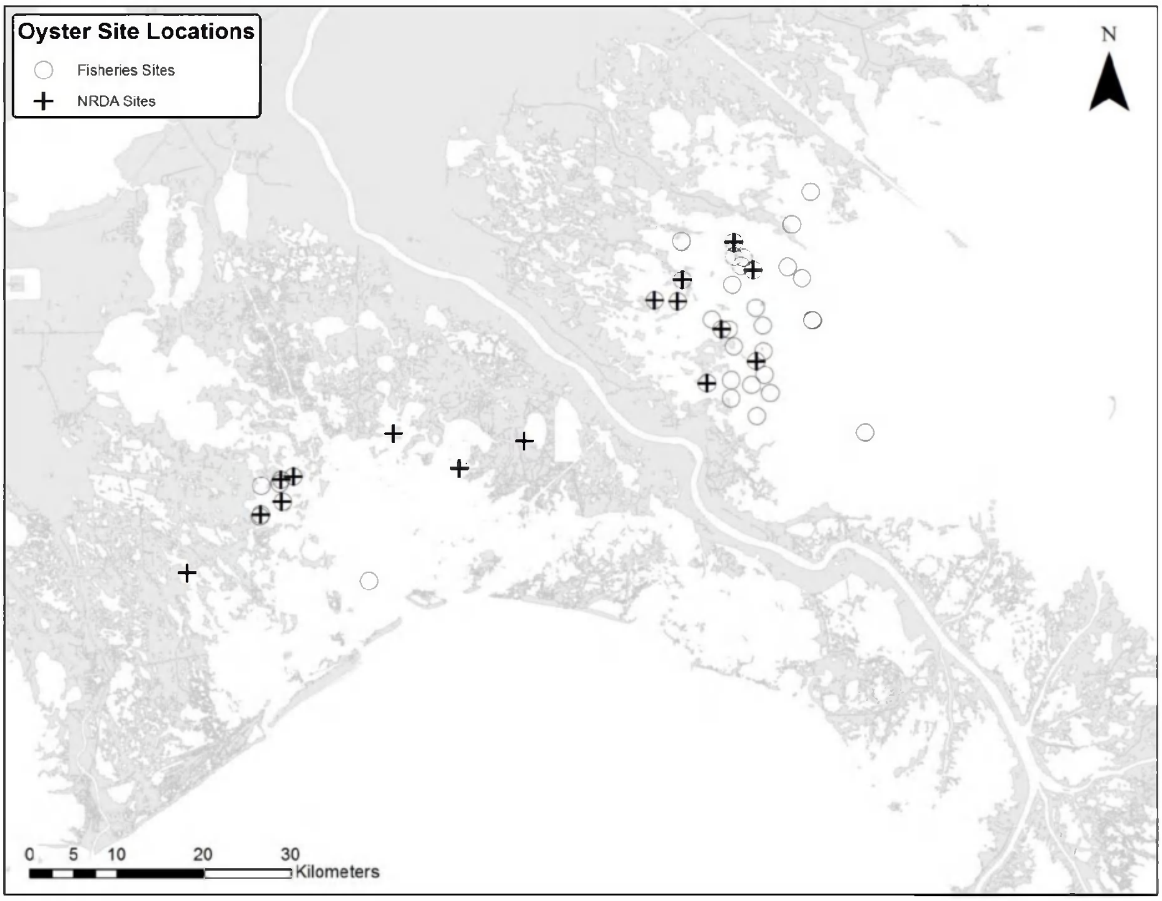

Figure 2 Oyster Density Sampling Locations (NRDA sampling; NOAA 2011)

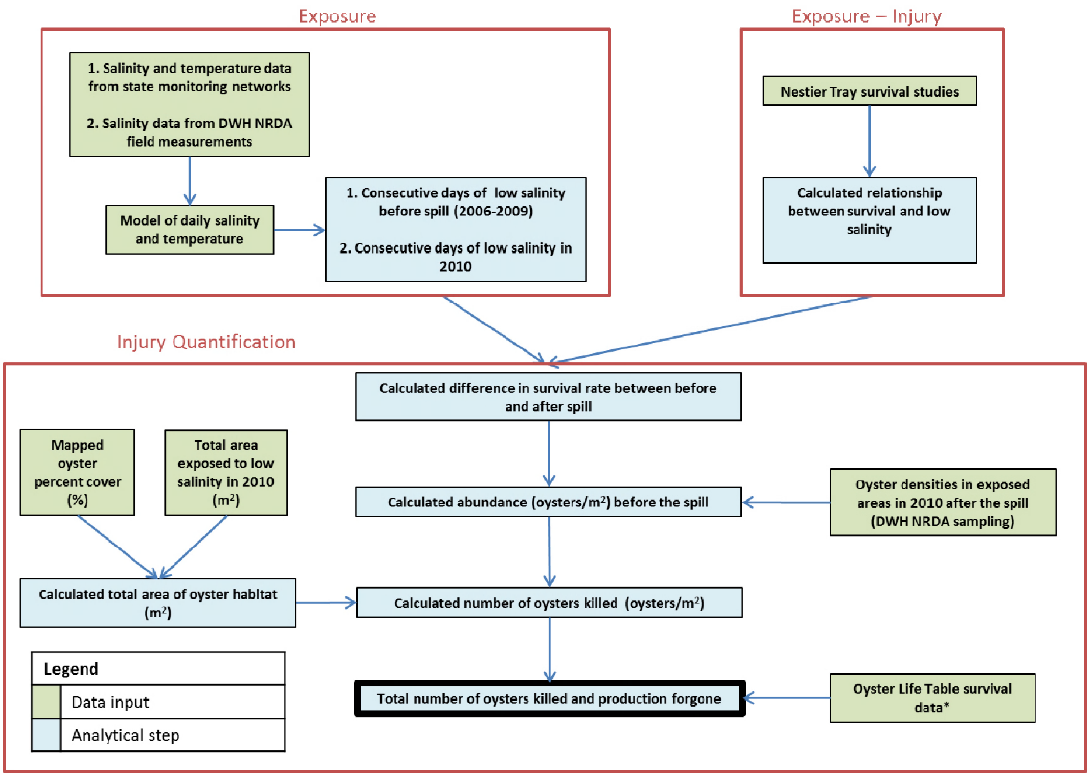

Figure 3. This diagram illustrates the analysis used to determine and quantify injury to oysters living in subtidal areas.

Top left box (Exposure): Thousands of salinity and temperature measurements were gathered and used to identify areas where salinity was unusually low in 2010 compared to prior years.

Top right box (Exposure – Injury): The relationship between exposure to low salinity and proportion of oysters that would die was determined from Nestier tray data.

Bottom box (Injury Quantification): Data on the percent cover of oysters and the abundance of oysters was used to calculate the number of oysters in the affected area before the spill, the number of oysters killed, and the number (and weight) of oysters that would have grown to adult stages if the spill had not happened.

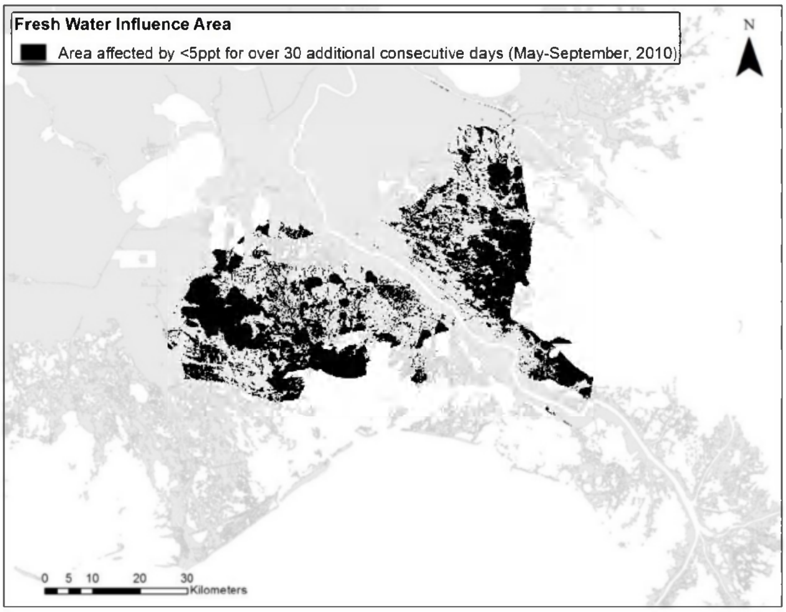

Figure 4. Locations in Barataria Bay and Black Bay/Breton Sound basins with more than 30 consecutive days below salinity thresholds of less than 5 parts per thousand in 2010 compared to baseline. These represent the influence of the river water releases in response to the *Deepwater Horizon* spill (Rouhani and Oehrig, 2015).

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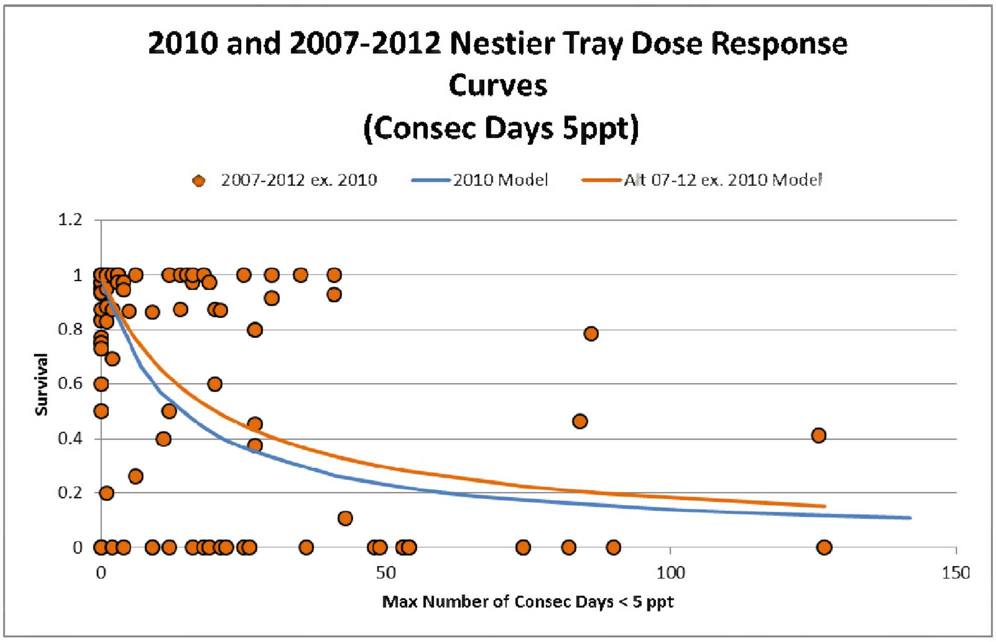

Figure 5. This graph shows the relationship between exposure to freshwater and oyster survival. As the number of consecutive days below 5 parts per thousand (average daily mean) increases (horizontal axis), survival of oysters drops (vertical axis) and more oysters die (Rouhani and Oehrig 2015). For example, a survival of 0.400 means that out of 100 oysters, 40 would be alive and 60 would die. The curve is derived from exposure and survival data from annual Nestier Tray oyster studies conducted in the Barataria Bay and Black Bay/Breton Sound basins by Louisiana Department of Wildlife and Fisheries.

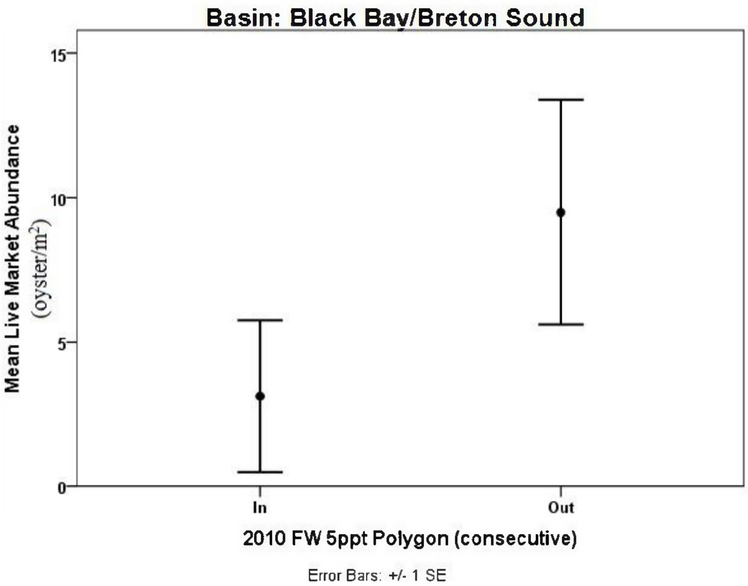

Figure 6. This graph compares the abundance of live market sized oysters per square meter (vertical axis) in Breton Sound areas affected and areas not affected by the river water releases (horizontal axis), as observed during the NRDA field study in 2010. The areas affected are those shown in black in **Error! Reference source not found.**, where salinities dropped below 5 parts per thousand for an unusually long period. The average in the affected areas is lower than in unaffected areas (Powers et al. 2015).

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